Cleaner fuels to reduce emissions of CO_2, NO_x and PM_{10} by container ships: a solution or a Pandora's Box?

J. M. Vleugel[1] & F. Bal[2]
[1]*Faculty of Civil Engineering and Geosciences, TU Delft, The Netherlands*
[2]*RISSK, The Netherlands*

Abstract

Transport vehicles contribute to the ongoing rise in emissions of CO_2 worldwide and emit large amounts of NO_x and PM_{10}. The growing demand for container transport is only sustainable if transport becomes 'greener'. There are innovations, which unite economic and environmental interests. One example is the ongoing increase in ship size, which reduces the cost of shipping by reducing fuel consumption and emissions per container. Another example is the use of alternative fuel (blend)s in ship engines.

The central theme in this paper is to better understand the impact of replacing standard fuels in engines of large(r) container ships by alternative fuels (biodiesel, LNG/CNG) on CO_2 NO_x and PM_{10} emissions. This leads to the following questions: Can alternative fuels help to significantly reduce CO_2, NO_x and PM_{10} emissions in port areas? Does their use allow compensation of the growth in emissions due to the growth in container shipping?

It is shown for a typical seaport container terminal that cleaner fuels can contribute to lowering these emissions, even if the volume of containers handled by this terminal triples. The use of what seems, at first glance, to be cleaner fuels may, however, open a Pandora's Box as a widespread use of organic biofuel may create other serious environmental problems, additional pressure on local food supply and social stability in already vulnerable areas of the world. More use of natural gas also raises serious environmental concerns.
Keywords: climate change, emissions, container transport, ports, fuels, trade-offs.

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1 Introduction

1.1 Emissions and policies

Container shipping is faced with many challenges; economic conditions, technical innovations, environmental impact and regulatory regimes.

The environmental impact of sea transport has been under focus since the first MARPOL resolutions were adopted in November 1973. What started with protection against oil spills and illegal garbage disposal has gradually been extended towards prevention of air pollution by ships in some parts of the world. So-called Emission Control Areas (ECA's) have become effective in the Baltic Sea (SO_x, 2006), the North Sea (SO_x, 2007), the North American waters (SO_x NO_x and PM_{10}, 2012) and the Caribbean Sea (SO_x, NO_x and PM_{10}, 2014) (IMO [1]). They target ships passing through littoral water and port areas.

The volume of TEU handled globally in 2033 will be much higher than today. For individual ports the growth scenario may differ, but for Rotterdam a tripling of the volume in 2008 is mentioned by Geerlings and Van Duin [2].

1.2 Technical innovations

Sea shipping is a very competitive business. The lower the cost per container, the more competitive a shipping line is. Fuel cost has a large share in operating cost of a ship. Driving fuel cost down is a top priority for ship manufacturers. They introduce larger ships able to carry more containers with the same or lower amount of fuel. This and better exhaust cleaning techniques translate into lower emissions per container.

Another interesting innovation is the use of alternative, 'greener' fuels. In a diesel engine fuel is gasified before being burned. HFO (Heavy or Residual Fuel Oil) is widely used, because it is the cheapest and widely available fuel. But it is, as the name already suggests, also of the lowest grade. Burning this tar leads to the highest level of emissions. Cleaner distillates like MDO (Marine Diesel Oil) or MGO (Marine Gas Oil) are in use as well. A third category is Intermediate or IFO, which is not discussed here. In emission control areas, switching bi- or tri-fuel engines to MDO or MGO has become common in order to fulfil (S)ECA standards. Instead of turning diesel into gas, it is also possible to directly inject natural gas, with certain technical adjustments and changes in operational procedures. Gas is primarily used for heating buildings or for industrial processes. This could change if CNG (Compressed Natural Gas) or LNG (Liquefied Natural Gas) becomes more widely used in sea shipping.

1.3 Goal and research questions

This paper investigates the emission reduction potential of alternative fuels in large(r) container vessels under scenarios of exponential growth in demand for container shipping. The main questions to be answered are the following:

Does the use of cleaner fuels allow stabilization or even reduction of the emissions of CO_2, NO_x and PM_{10} in the year 2033 under a scenario of triple growth in container throughput? What are the pros and cons of their use?

1.4 Set-up of the paper

Section 2 contains the problem analysis. Section 3 explains the methodology deployed. In section 4, scenarios are used to estimate the potentially achievable emission reductions by selected fleet composition and alternative fuel scenarios. Conclusions and recommendations for next research steps can be found in section 5.

2 The system and the problem

2.1 Introduction

A simulation study is used to determine the emission reduction potential of alternative fuels used in container ships visiting a major seaport container terminal in Rotterdam. The terminal under study is ECT's Delta container terminal, which is located in the Europa Port/Amazone basin of the port of Rotterdam. This terminal is 265 hectares in size and its quay length is 3.6 km. It can discharge and load sea ships with a maximum depth of 16.65 m. Its 36 quay cranes allow handling of sea ships with a maximum span of 22 containers wide (ECT [3]). Existing equipment and operational practices allow a maximum landside capacity of 4.5 MTEU (million twenty feet equivalent units) per year. Actual capacity is reduced by downtime for maintenance, functional slack, seasonal usage patterns, strikes, congestion in hinterland networks and competition from other (adjacent) terminals. 3.08 million containers were handled at the Delta terminal in the reference year 2008 (Geerlings and Van Duin [2]).

2.2 Growth in container transport and its consequence

According to forecasts, the number of containers transported is likely to grow exponentially worldwide. A rise from 11 to 33 MTEU is mentioned for the port of Rotterdam for study year 2033 (Van Duin and Geerlings [4]). The new Maasvlakte 2 terminals should mainly accommodate this growth, but older terminals, like the Delta terminal at Maasvlakte 1, will have their fair share.

At the Delta terminal a much higher yearly throughput is feasible. Call sizes and quay crane productivity are on the rise. In 2012–2013 the Amazone basin has been widened and quays were strengthened in order to accommodate larger ships. The latest discharge and load record was 11.051 containers by a Thalassa class vessel from Evergreen (ND [5]). If this would become the norm, then a tripling in yearly volume handled is technically feasible with current technology. By combining more, larger, vessels with future container handling technology, the triple growth scenario is realistic. The productivity of other quay equipment and the hinterland transport systems (road, barge, rail) should rise correspondingly.

The impact of more visiting ships will be a rise in energy consumption and emissions by shipping and container handling equipment.

3 Methodology

3.1 Introduction

In this section the scope will be defined. Next the input-output simulation model and the scenarios will be introduced.

3.2 Scope

A container terminal is a highly complex operation, involving maritime and landside operations by its main stakeholders; the operators of ships, the terminals and the - not considered - hinterland transport modes – rail, road and barge.

The focus is on the energy consumption and the CO_2, NO_x and PM_{10} emissions with respect to the Delta terminal for specific maritime and quayside scenarios. It is assumed that terminal capacity is freely scalable.

3.3 The model

An input-output model was developed to simulate key functionalities of the Delta terminal and the emissions by its terminal handling equipment and visiting ships. It was developed using public specifications of the terminal and environmental data, such as emission factors of fuels. The model can be used to estimate CO_2, NO_x and PM_{10} emissions for specific container volumes, a set of handling equipment, fleet composition and fuel types.

3.4 Emission calculations

In general, the emission level EL of using a fuel can be specified as:

$$EL = \mathrm{G}(E, ef, t) \quad \text{with } EL, E, ef, t \in \mathbb{R}^{+} \tag{1}$$

where E is the amount and t is the time energy of type E is used. *ef* denotes the emission factor corresponding to this type of energy.

Seaports are close to the sea, but each visiting ship needs time to deviate from a shipping route, enter littoral waters, then the port and finally stop at the berth where containers are discharged and loaded. This paper considers energy use between the moment a ship enters the port until (and including) it stays at the quay (berthing) (and vv).

3.4.1 Entering a port

In general, the emission level due to maritime activity (for short, EL^M) by a single ship i can be specified as:

$$EL_i^M = E_i \times ef_i \times t \quad \text{with } EL, E, ef, t \in \mathbb{R}^+ \tag{2}$$

where E is the time fuel type used, again, t is the time span when this source of energy is used and ef denotes the emission factor commonly measured in gram/litre (g/ltr) or gram/kWh (g/kWh).

3.4.1.1 Hoteling (berthing) During hoteling two power options are relevant:

1. Continue to use the ships on-board power system.
2. Switch from the on-board power system to shore power.

In case of (2), the emission level during hoteling (for short, EL^H) can be estimated for both power source alternatives.

Several remarks can be made regarding energy use and emissions in a port. First, in general, less energy is needed per ship if it stays in the port compared to when it is at sea (Conoship [6], Kontovas and Psaraftis [7]). Second, different power sources (HFO, MDO/MGO or electricity) have different emission factors; hence their emission levels vary. Third, the time that a ship is stationary depends on:

- the number of TEU that needs to be transferred between the ship and the terminal per port call;
- the speed with which these TEU can be exchanged.

The speed of the cranes (barge cranes (BC) and quay cranes (QC)) critically determines the so-called turn-around time of the visiting vessel and, hence, the overall emission levels per port call.

ECT does not provide (detailed) terminal handling data. As a proxy, the yearly throughput was translated into a potential ship-handling scenario. The simulated data can be found in Table 1.

Table 1: Data used in the terminal handling scenarios.

Vessel class	Average length (in meters)	TEU exchanged per visit	Average TEU/hour/QC	QC#
Short Sea Ship	150	650	55	2
Panamax	280	1,100	55	4
Post-Panamax	335	2,800	55	5
Suezmax	400	3,300	55	5
Post-Suezmax	470	4,950	55	6
			Average TEU/hour/BC	BC
Other	120	0	55	0
Barge	120	70	55	2

3.4.2 Turn-around time

The turn-around time (t^{TA}) for ship i is equal to:

$$t_i^{TA} = t_i^M + t_i^H . \tag{3}$$

with t^M being the manoeuvring/sailing time from the port entrance to the berth (times 2) and t^H the handling time of the planned number of TEU per port call.

When estimating the turnaround time, the average number of TEU to be exchanged and the terminal handling capacity must be taken into account. This results in the next equation:

$$t_i^{TA} = t_i^M + t_i^H = t_i^M + \frac{T_i}{aQ \times n} \quad \text{with } T, aQ, n \in \mathbb{N}. \tag{4}$$

where T denotes the number of TEU per ship of class i that call the port, aQ denotes the average number of TEU that a single quay crane (BC, QC) of the terminal can transfer per hour and n is the number of quay cranes in simultaneous operation to discharge and load a ship of class i. Table 1 provides an indication about the relevant parameters of t^H in (4).

The larger the vessel, the more TEU is likely to be exchanged per call.

The total emissions by ships of type i per port call is equal to:

$$EL_i = EL_i^M + EL_i^H. \tag{5}$$

Hence,

$$\begin{aligned} EL_i &= EL_i^M + EL_i^H \\ &= (E_i^M \times ef_i^M \times t_i^M) + (E_i^H \times ef_i^H \times t_i^H) \\ &= \left(E_i^M \times ef_i^M \times (t_i^{in} + t_i^{out})\right) + \left(E_i^H \times ef_i^H \times \frac{T_i}{aQ \times n}\right). \end{aligned} \tag{6}$$

Equation (6) may be used to mimic the impact of fuel scenarios, emission factors as well as the call times for ships of class i. A weekly window is assumed for visiting vessels of a certain class. This regular pattern allows estimation of emissions by multiplying the weekly port calls with the number of weeks in a year, viz. 52.

4 Scenarios and emissions

4.1 Introduction

Sea ships use their main engine(s) to enter the port and may use the same engine(s) or (an) on-board auxiliary engine(s) to generate the electricity for the ship support systems during hoteling. Different hoteling scenarios can be made depending on the port regime, the port facilities and the on-board facilities. These scenarios lead to alternative emission scenarios. Decision makers are able to see their potential by comparing the hoteling scenarios.

4.2 Reference scenario (2008)

The main engine is the prime energy consumer, hence prime source of air pollution by a container ship. As Table 2 shows clearly, a switch from HFO to MDO results in just a slight reduction in CO_2- and NO_x emissions. The reduction in PM_{10} emissions is much higher. This can be explained by the lower sulfur content of MDO. Reducing PM_{10} emissions is very important, because these have a major negative health impact for those living in the region surrounding the terminal.

Table 2: Emission estimates by manoeuvring and hoteling ships consuming HFO or MDO if 3.08 MTEU are transferred annually (in 2008).

	CO_2 (kg/year)	NO_x (kg/year)	PM_{10} (kg/year
Fuel type			
HFO_{2008}	16,801,566	342,082	34,906
MDO_{2008}	16,253,666	328,384	13,504

Regarding the Delta container terminal, visiting ships may contribute on average about a quarter to its aggregated emissions. This share is changing over time because terminal equipment also becomes more energy efficient, hence (relatively) cleaner over time. For instance, diesel engines are replaced by electric or hybrid diesel-electric ones.

4.3 Alternative scenario 1: triple TEU and same ship sizes (2033)

Around 2033 the volume of TEU handled in the port of Rotterdam may triple compared to 2008. Hence, large logistic and environmental challenges are ahead.

Which opportunities are there to avoid a major increase in emissions? In other words, what are the opportunities to triple the handling of containers at this container terminal and still maintain the emission levels of 2008? This section will investigate the options to achieve a zero growth scenario for emissions based on techniques in use today.

Scenario I: port calls with the same ship type diversity, times three. Tripling the dispatch of containers would imply a volume of 9.24 TEU in 2033. Assuming that the logistic relationships between in- and outgoing container flows stay the same, this growth would translate into triple the number of visiting vessels. Table 3 gives the emission estimates for the year 2033. As expected, the emissions triple compared to the benchmark (cf Table 1).

Table 3: Emission estimates by manoeuvring and hoteling ships consuming HFO or MDO if 9.25 MTEU are transferred annually (in 2033).

	CO_2 (kg/year)	NO_x (kg/year)	PM_{10} (kg/year)
Fuel type			
HFO_{2033}	50,404,697	1,026,245	104,719
MDO_{2033}	48,760,998	985,153	40,512
HFO_{2008}	16,801,566	342,082	34,906

Note: 9.25 were used instead of 9.24 because of rounding off (whole ships).

Biofuels. Biofuels are already in their third generation (algae). In engines first (biodiesel, etc.) or second (biomass, etc.) generation are common. The most widely spread first generation version will be analyzed. In most of the existing ship engines biodiesel can be used as blends of diesel (or methanol or ethanol) with a certain percentage of biofuel (e.g. B_{10} with 10%). Use of pure biofuel (B_{100}) is not likely yet, because of technical and economic reasons. Biofuels have a rather different chemical composition than diesel: a lower caloric value (lower efficiency), a higher viscosity (lower atomization), inherent oxygen (up to 11%, which allows a leaner burning) and higher cetane number. These differences have a moderately negative to neutral impact on fuel consumption (Dwivedi *et al.* [8]).

Biofuels have many advantages in terms of air pollution – no SO_2, substantially less CO_2, less HC and CO and reduced impact of oil spills. NO_x emissions may increase slightly (Opdal and Hojem [9]). There is, however, other environmental concerns, which will be discussed in the evaluation section of this paper. Practical issues with biofuels are a currently limited availability and higher cost of handling and maintenance (tank cleaning and filter cleaning). What also works against biofuels is that by consuming low or ultra-low sulfur fuels ships can fulfill current emission permits (Nayyar [10]).

A retrofit of existing ships may be (too) expensive. With an average build time of 38 weeks per vessel, enrolling ships with more modern engines is not a problem. The average life of a sea going container vessel is about 20 years. This means that it may take a while before the existing fleet of sea container ships is replaced. In case of a triple growth in container volumes, more drastic measures are necessary. This is why in the next scenario B_{100} and LNG are considered, again for the current fleet visiting the terminal. Table 4 shows the estimates.

Table 4: Emission estimates by manoeuvring and hoteling ships consuming biodiesel B_{100} or LNG if 9.25 MTEU are transferred annually (in 2033).

	CO_2 (kg/year)	NO_x (kg/year)	PM_{10} (kg/year)
Fuel type			
$B100_{2033}$	17,390,319	83,705	5,403
LNG_{2033}	25,272,161	119,380	24
HFO_{2008}	16,801,566	342,082	34,906

None of the cleaner fuels can (fully) compensate the increase in emissions due to a triple volume of TEU exchanged at the terminal. B_{100} would be the first best solution, but LNG is a more practical second best solution. Significant reductions in NO_x and PM_{10} are feasible. LNG has the advantage of a lower price and lack of distortion of agricultural markets and the environment, which are typical for organic biofuels (Kolwzan and Narewski [11]). What works against LNG is 4–5 times larger storage tanks onboard a ship (Nayyar [10]).

The ongoing increase in ship sizes, the ability to carry more TEU per ship and taller and more productive equipment at the terminal make a scenario of constant ship sizes and fleet composition not a very realistic one. The average operational life of about 20 years means that part of the ships currently visiting Rotterdam harbor will be decommissioned before 2033. This leads to scenario 2.

4.4 Alternative scenario 2: triple growth and larger ships

Scenario II: port calls with (Post) Panamax ships replaced by (Post) Suez ships. In this case it is assumed that around 20 years from now ships visiting the container terminal are evenly divided over Suez and the post-Suez classes. For simplicity, it is assumed that the (post-)Suez ships use the same amount of energy, but are able to carry more TEU than their predecessors. Regarding the other types of vessels (e.g. barges, short sea ships it is assumed that they do not change in size due to technical restrictions in ports and waterways. The number of other visiting ships such as barges is considered to be triple the 2008 levels.

In this scenario only the use of pure biodiesel will result in emissions (see Table 5) of CO_2 that are lower than those of 2008. LNG will lead to a modest rise in CO_2 and NO_x emissions compared to the benchmark. Emissions of PM_{10} are much lower, though. LNG is a practical alternative for B100. This explains the interest of ship owners in this fuel.

Table 5: Emission estimates of manoeuvring and hoteling ships using various fuels if 9.36 MTEU are transferred annually (in 2033).

	CO_2 (kg/year)	NO_x (kg/year)	PM_{10} (kg/year)
Fuel type			
HFO_{2033}	40,164,571	817,755	83,444
MDO_{2033}	38,384,424	773,251	13,907
$B100_{2033}$	13,857,333	66,700	4,307
LNG_{2033}	20,137,915	95,127	1,925
HFO_{2008}	16,801,566	342,082	34,906

Note: 9.36 TEU was used instead of 9.25 TEU because of rounding off (to whole ships).

Scenario III: Scenario II with shore power. In this case shore power (electricity) is used to power the ships support systems during hoteling. This leads to another reduction in emissions. The emission factors from the current Dutch energy mix are used (Essent [12]). The results can be found in Table 6.

When the percentage of green sources in the electricity mix increases, emission factors continue to improve (Gijsen and Spakman [13]), which leads to a further reduction of emissions.

4.5 Evaluation

Several scenarios were tested to see if the emissions of CO_2, NO_x and PM_{10} can be stabilized when the yearly throughput of a seaport container terminal triples. It may take some effort to achieve this. Emissions per container can be reduced by the introduction of larger ships. However, growth of container transport is

Table 6: Emission estimates of future ships using various fuels for manoeuvring and shore power from the grid during hoteling if 9.36 MTEU are transferred annually (in 2033).

	CO_2 (kg/year)	NO_x (kg/year)	PM_{10} (kg/year)
Fuel type			
HFO_{2033} + Shore $power_{2033}$	9,235,824	188,042	19,188
MDO_{2033} + Shore $power_{2033}$	8,826,480	177,809	3,198
$B100_{2033}$ + Shore $power_{2033}$	3,186,487	15,338	990
LNG_{2033} + Shore $power_{2033}$	4,630,704	21,874	443
HFO_{2008}	16,801,566	342,082	34,906

such that only a shift to cleaner fuels may neutralize the growth in emissions. Even an absolute reduction in emissions is feasible in the most effective scenario, but the way this could be achieved may raise serious questions.

A switch from the micro level of this terminal to the macro level, the world level, changes the colour of the outlook to grey or even black. More use of biofuels is debateable, at least if produced from organic matter. Table 7 contains an overview.

Table 7: Organic biofuels: major issues.

Issue	Details	Solution
Steep price	+/- 2x MDO	CO_2 tax deduction
Production and availability	< 1% of consumption	More production
Environment[1]	Land use Deforestation Lower biodiversity Acidification Over-fertilisation Increase in agricultural diseases	Non-organic alternatives
Social, health	Competition Less food for higher prices Social instability	Non-organic alternatives

Note 1: SFLMST [14].

More use of natural gas (CH_4 converted into LNG or CNG) is also not without environmental risks and consequences, because the GWP of natural gas is several times higher than the GWP of CO_2. Gas leaks are rather common and both conventional and more modern production methods like fracking with chemical solvents carry substantial risks for the environment and water resources (Tollefson [15]).

Finally, emissions to the air are also partially caused by terminal handling equipment and auxiliary systems for lighting and temperature controlled containers (reefers). On-going electrification and higher energy efficiency help to mitigate their emissions, but once the potential at the quay disappears, (even) more should happen at the marine side of the terminal.

5 Conclusions and recommendations

This paper was meant to answer a few seemingly straightforward questions. The further we progressed, the more we realised that the topic is much more complex than it looked like when we started.

Going back to the initial research question, the answer is, yes, it is possible to substantially reduce the emissions to the air by container ships in port areas, even if the volume of containers transported grows exponentially.

The catch is that what seem effective options to cure the problem of growing emissions may also create new environmental and social problems. Effective environmental policy should be about solving and not shifting large problems to other (poorer, more vulnerable) parts of the world in our opinion.

It would be interesting to carry out further research using dedicated terminal data and data about hinterland transport and then to work on evaluations of life tests with seagoing vessels.

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